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Fertilizer induced nitrous oxide emissions from Vertisols and Alfisols during sweet sorghum cultivation in the Indian semi-arid tropics

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HIGHLIGHTS

- First report on N_2O emissions from agriculture soils in the Indian semi-arid region.
- Applied N lost as N_2O from Alfisols and Vertisols was 0.90 and 0.32% respectively.
- N_2O emissions are dependent on the soil properties.

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ABSTRACT

Nitrous oxide (N_2O) emissions from Vertisols and Alfisols during sweet sorghum cultivation in the Indian semi-arid tropics were determined using a closed chamber technique during the rainy season (June–October) of 2010. The study included two treatments, nitrogen (N) at a rate of 90 kg/ha and a control without N fertilizer application. The N_2O emissions strongly coincided with N fertilization and rainfall events. The cumulative N_2O–N emission from Alfisols was 1.81 N_2O–N kg/ha for 90 N treatment and 0.15 N_2O–N kg/ha for the 0 N treatment. Similarly, the N_2O–N emission from Vertisols was 0.70 N_2O–N kg/ha for 90 N treatment and 0.09 N_2O–N kg/ha for the 0 N treatment. The mean N_2O–N emission factor for fertilizer induced emissions from the Alfisols was 0.90% as compared to 0.32% for Vertisols. Our results suggest that the N_2O emissions are dependent on the soil properties. Therefore, the monitoring of N_2O emissions from different agro-ecological regions, having different soil types, rainfall characteristics, cropping systems and crop management practices are necessary to develop comprehensive and accurate green house gas inventories.

1. Introduction

Nitrous oxide (N_2O) is an important trace gas that causes global warming and stratospheric ozone depletion. The global atmospheric N_2O concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005 (Intergovernmental Panel on Climate Change, IPCC, 2007), and this increase is thought to be due to anthropogenic emissions of greenhouse gases (GHGs). Globally, agricultural soils account for about 60% of the atmospheric N_2O emissions (Mosier et al., 1998; Kroeze et al., 1999). In agricultural soils, N_2O is mainly generated from mineral N originating from applied N fertilizer, mineralization of soil organic N and biologically fixed N_2 (Freney, 1997). Among these, the application of reactive N in the form of synthetic fertilizers is considered a primary source of N_2O emissions from agricultural soils (Mosier et al., 1998; Mosier and Kroeze, 2000). Nevertheless, N fertilizers are essential to face the rise in food requirements for a burgeoning human population coupled with the reduction in agricultural land. Thus, it can be anticipated that with the accelerating demand for N fertilizers the current trend of increasing atmospheric N_2O concentrations will likely to continue over the next several decades.

In recent years, rapid changes in land-use are taking place in tropical Asia, which may cause changes in the amounts of emission of GHGs from terrestrial ecosystems. Mosier and Kroeze (2000) estimated that the N_2O emissions to the atmosphere would increase about 1.4 times between 1990 and 2020, with much of this increase projected to occur in Asia. India is the second largest producer and consumer of N fertilizer in the world (Prasad, 2012). The Ministry of Environment and Forests (MoEF), India (2007) estimated the GHGs emissions from agriculture to be 17% of the net CO_2 equivalent emissions of the total GHGs emissions.

The demand for energy in India is growing at an annual rate of 4.8% (Agoramoorthy, 2012). Biofuels are being promoted widely as a solution to rising fuel prices, growing energy demands and to cut the emissions of GHGs. Recently, there has been a lot of impetus on the use of feed stocks that are non-food grain and that can grow on marginal

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and abandoned lands. Sweet sorghum (*Sorghum bicolor* (L.) Moench) is one such crop that is gaining global interest as a feedstock for biofuel production as it can be grown under widely differing climatic conditions (Rao et al., 2009). Given the current interest in commercial and large-scale exploitation of sweet sorghum as a bio-ethanol crop and with the anticipated increase in N inputs, there is a risk that N_2O emissions from high N applications will reduce the GHG advantages sought from biofuel production.

The primary objective of this study was to quantify the N fertilizer-induced N_2O emissions during the sweet sorghum growing season. As agricultural N_2O emissions are generally dependent on soil types, the study was conducted in two soil types, Alfisols (Ferric Luvisol, FAO classification; Udic Rhodustalf, USDA classification) and Vertisols (Pellic Vertisol, FAO classification; Typic Pellustert, USDA classification). Furthermore, though semi-arid and arid lands constitute a large part of the global land area and are widely used for agricultural production, there are few studies relating to N_2O emissions from semi-arid agricultural soils (Barton et al., 2008, 2010; Pang et al., 2009). Thus, this study was carried out to understand the N_2O fluxes from agricultural soils in semi-arid regions to assess the GHG emissions from this particular bioenergy cropping system. The study may aid in future recommendations for reducing N_2O emissions from sweet sorghum farming.

2. Materials and methods

2.1. Study location and description of the experiment

The study was carried out at the farm of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India located at 17°53′N and 78°27′E, at an altitude of 545 m above mean sea level during the rainy season of 2010 (June–October). The climate of the region is subtropical and semi-arid. The area receives an annual rainfall of 800 mm, about 80% of which occurs from June to September. Soil properties (0–15 cm depth) of the experimental fields are reported in Table 1.

The present study included two treatments, N at a rate of 90 kg/ha and a control without N fertilizer application. The treatments were assigned as a randomized block design with three replications and each plot measured 8 m long and 6 m wide. Urea (46% N) was applied at the rate of 90 kg N/ha in three split doses, i.e. 15 kg N/ha (basal), 37.5 kg N/ha (1st top-dressing) and 37.5 kg N/ha (2nd top-dressing) at 0, 30 and 60 days after sowing (DAS). Nitrogen fertilizer was applied in splits at a depth of 5 cm on each side of the plant row, and covered with soil. Other nutrients (phosphorous (P): 40 kg P_2O_5 ha^{-1}, sulfur (S): 200 kg gypsum ha^{-1}, B: 0.475 kg B ha^{-1}, Zn: 50 kg $ZnSO_4$ ha^{-1}) were incorporated into the soil at sowing of the crop. Promising sweet sorghum hybrid in India "CSH 22 SS" (Rao et al., 2009), was grown on the ridges landform 20 cm apart and with an inter row width of 60 cm with a planting density of 8.3/m^2. Sowing was done on 10th June and 22nd June 2010 in Vertisols and Alfisols, respectively.

Table 1
Properties of the soils at 0–15 cm depth.

	Alfisols	Vertisols
Particle size classes		
% Coarse sand 0.2–2 mm	44.1	12.5
% Fine sand 0.02–0.2 mm	27.5	13.9
% Silt 0.002–0.02 mm	7.1	22.1
% Clay<0.002 mm	21.3	51.5
FAO classification	Ferric Luvisol	Pellic Vertisol
pH (H_2O)	7.8	8.3
EC (dS/m)	0.22	0.18
Total N (mg/kg)	755	560
Organic C %	0.50	0.57

2.2. Gas sampling

A cylindrical stainless steel chamber, 0.20 m in diameter and 0.16 m high, was used for the collection of gas samples. Two chambers were installed in each plot, one chamber was placed on the ridge and another in the furrow. Chambers were installed at least 24 h before sampling, and left in situ, except for when they had to be removed temporarily for carrying out farming operations. Chambers were left uncovered throughout except for during the periods when gas samples were collected. The chambers were inserted to a depth of up to 3 cm to ensure an airtight seal. The surface area enclosed by the chamber was 0.031 m^2. Samples were collected between 08.00 and 11.00 AM, thrice weekly, following N fertilization when the potential for N_2O emissions was higher due to the availability of N substrate. Sampling frequency was reduced following 2 weeks after fertilization when the emissions fell close to background levels. The sampling process consisted of manually extracting samples from the headspace of the chamber through a septum using a 25 ml polypropylene syringe at 0, 15 and 30 min after closure and transferring the air samples to pre-evacuated 12 ml Exetainers vials (Labco Limited, UK) fitted with a butyl rubber stopper and a screw cap. Atmospheric samples were also collected to provide background values for N_2O.

2.3. Analysis of nitrous oxide

N_2O concentrations were determined using a gas chromatograph (Shimadzu, GC-2014, Japan) equipped with a ^{63}Ni electron capture detector (ECD) and switching valves. Separation was performed using stainless-steel columns packed with 80/100 mesh Porapak-Q. The column oven, injection port and detector temperatures were set at 80 °C, 150 °C and 280 °C, respectively. Nitrogen gas at a flow rate of 65 ml/min was used as the carrier gas. A mixture of argon (Ar) gas containing 5% CH_4 was added to the N_2 carrier gas flow before the detector to increase the sensitivity of the detector. N_2O fluxes were calculated from the rate of change in the concentration of N_2O in the air inside the chambers during the time of sampling. This was estimated by the slope of the linear regression between concentration and time and from the ratio between chamber volume and soil surface area. Cumulative N_2O fluxes were determined by linearly interpolating data points between each successive sampling event, and integrating the underlying area.

2.4. Statistical analysis

Statistical analysis was conducted using the SPSS software (version 12.0E, SPSS Japan). Analysis of variance (ANOVA) was performed by combined model (McIntosh, 1983). Fields (Alfisols and Vertisols), N treatments (0 and 90 N) and position of chambers (ridges and furrows) were treated as fixed factors, and replication as a random factor.

2.5. Ancillary measurements

Soil samples were collected before sowing to determine physical and chemical properties of the soil. The samples from each plot were mixed, dried and sieved.

Meteorological data on mean air temperature and precipitation were obtained from the ICRISAT weather station in Patancheru, India.

3. Results and discussion

3.1. Climate conditions

The average daily maximum temperature was 30 °C, and ranged from 24 °C to 37 °C during the growing period, while the average daily minimum temperature was 23 °C and ranged from 19 °C to

25 °C throughout the growing period (Fig. 1). The total rainfall received during the growing period was 941 mm. Rainfall was well spread during the growing season and furrow irrigation was conducted only once in both the fields. The maximum amount of rainfall was received during August (Fig. 1). This resulted in many periods of high soil moisture content.

3.2. Emissions of N_2O–N

Nitrous oxide emissions are episodic in nature. The application of N and wet soil conditions after high precipitation are usually followed by periods of high N_2O emissions (Sahrawat and Keeney, 1986). In the present study, the schedule of gas sampling was planned accordingly to observe N_2O emissions frequently for 2 weeks after N applications. Figs. 2a and 3a show the temporal variations in N_2O emissions from the ridges in the Vertisol and the Alfisol fields, respectively. Similarly, Figs. 2b and 3b show the temporal variations in N_2O emissions from the furrows in the Vertisol and the Alfisol fields, respectively. A summary of cumulative N_2O fluxes from the various treatments is presented in Table 2. Analysis of variance indicated the significant effect of fertilizer N on cumulative N_2O fluxes ($P<0.01$). Also, there was significant field-by-N treatment interaction ($P<0.05$) suggesting that N_2O emissions increased with the application of fertilizer N in both Alfisols and Vertisols, but it increased more largely for Alfisols than for Vertisols. Results from the two study sites showed a consistent pattern in N_2O emissions. As in most previous studies (Watanabe et al., 2000; Hellebrand et al., 2008; Fernández-Luqueño et al., 2009), N_2O emissions were stimulated following N fertilization. The addition of urea significantly increased N_2O emissions compared to the unfertilized plots, by providing additional substrate for nitrification and/or denitrification. A significant effect of the placement of chambers on ridges and furrows on cumulative N_2O fluxes was observed ($P<0.01$). As urea was applied only to the ridges, higher N_2O emission rates just after fertilization occurred from the ridges than from furrows. Similar to the results of this study, N_2O fluxes from rows planted to soybeans were significantly higher than that in between rows in the Midwest United States (Parkin and Kaspar, 2006). However, McTaggart and Smith (1996) found N_2O emissions from furrows to be larger than that from the ridges though N was applied into the ridges. Such a phenomenon was attributed to a combination of fertilizer N movement from the ridges to furrows by leaching and diffusion with higher soil moisture content in the furrows.

3.3. Emission of N_2O–N from Vertisols

Immediately after the application of urea, N_2O emissions were commonly elevated for the first few weeks and then declined to approach background values. Sahrawat (1984) reported that the hydrolysis of urea was rapid in the semi-arid tropical soil, almost all the urea was hydrolyzed within 24 h of application, at soil moisture content near field capacity and at soil temperatures of 27–37 °C. The hydrolysis of urea followed by nitrification and denitrification are the most important processes that contribute to the emission of N_2O from the soil. The highest value of N_2O flux for the 90 kg N/ha treatment was 355 N_2O–N μg/m^2/h, which occurred after the second topdressing (Fig. 2a). After the N_2O emission peaks, which were followed by second top dressing, the N_2O emissions reached and stayed at the background levels until harvest of the crop. Nitrogen fertilization appeared to be the most important factor that stimulated N_2O emission. The N_2O emissions from the furrows were considerably less compared to that from the ridges (Fig. 2b). The cumulative N_2O–N emission during the cultivation of sweet sorghum was 0.70 N_2O–N kg/ha for 90 N treatment and 0.09 N_2O–N kg/ha for the 0 N treatment.

3.4. Emission of N_2O–N from Alfisols

As in the case of the Vertisol, a similar trend in N_2O emissions was observed for the Alfisol. The N_2O fluxes generally increased sharply after N-fertilizer additions before tailing off to low values, until the next fertilizer addition. The mean highest flux was 1570 N_2O–N μg/m^2/h, observed after the second top-dressing (Fig. 3a). The magnitude of N_2O emission from soil depends not only on the availability of N but also on other factors such as soil temperature, soil aeration, availability of carbohydrates, pH and soil water content (Sahrawat and Keeney, 1986). Because of the frequent rainfall throughout the growing season, it resulted in many periods of high soil moisture content, which favored the production of N_2O. The large peaks of N_2O flux were observed in response to rainfall events after the application of urea (Figs. 1 and 3a). The high N_2O fluxes might have been caused by active nitrification after N application under high moisture condition. As the N_2O emissions were seen soon after the application of urea, it is suspected that nitrification was the dominant processes in the emissions of N_2O in this study. The N_2O emissions from the furrows were comparable to that from the unfertilized plots (Fig. 3b). The cumulative N_2O–N emission during the sweet sorghum cultivation

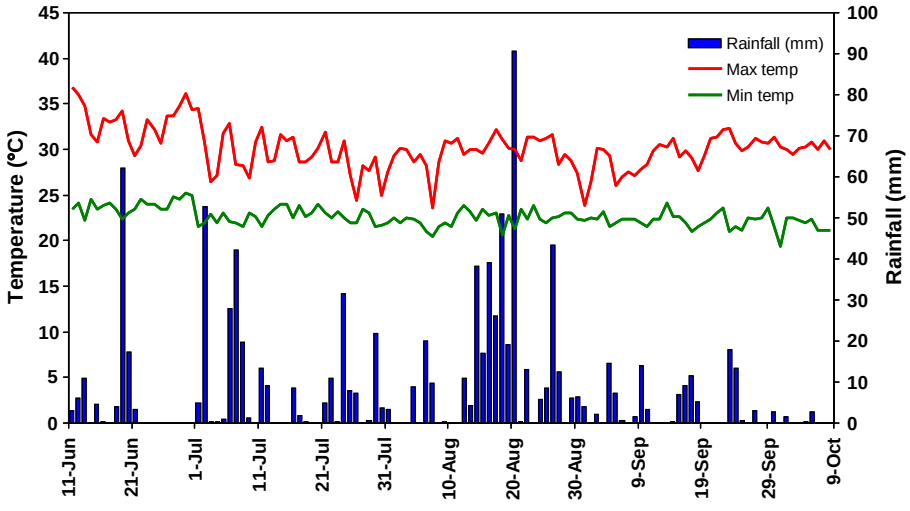

Fig. 1. Variation in temperature and rainfall during the Kharif season 2010.

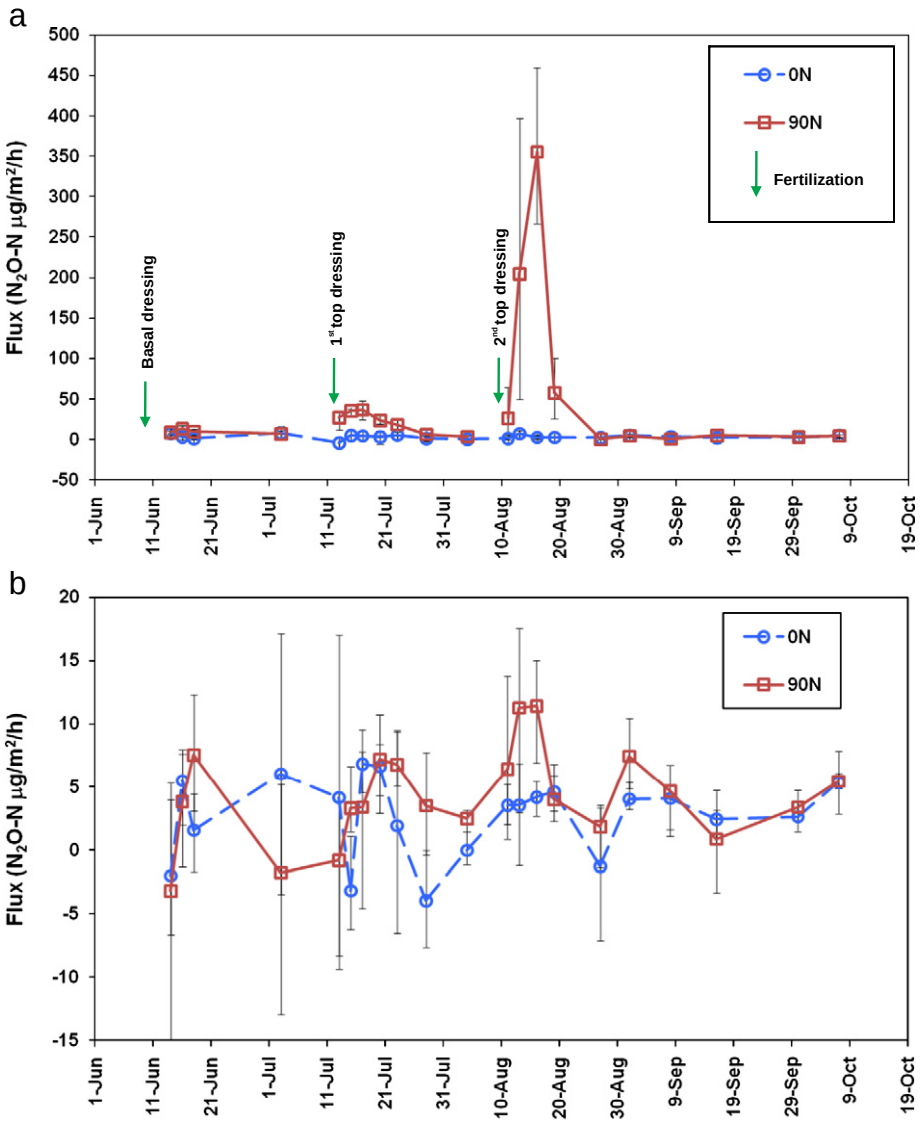

Fig. 2. Changes in N_2O emissions from (a) ridges (b) furrows on Vertisol field cultivated with sweet sorghum. The vertical bars show the range of the flux in triplicate measurements. 0 N: represents N_2O emissions from plots with no nitrogen application; 90 N: represents N_2O emissions from plots fertilized with 90 kg N/ha.

was 1.81 N_2O–N kg/ha for 90 N treatment and 0.15 N_2O–N kg/ha for 0 N treatment.

3.5. Variation in N_2O–N emissions between Vertisols and Alfisols

The difference in N_2O emissions between these two soils provides evidence that N_2O emissions from fertilizers are significantly influenced by interactions with other factors such as the soil physical and chemical properties. The underlying causes of higher N_2O fluxes from Alfisols when compared to the Vertisols might be attributed to the differences in the soil characteristics such as organic C and nitrogen pools, water-holding capacity, pH, texture and microbial community structure. In the current study, the initial total N in Alfisols and Vertisols was 760 and 560 mg/kg soil, respectively. This suggests that the higher soil total N in Alfisols might have provided adequate amounts of NO_3^- and NH_4^+ to the substrate pool following N mineralization. A negative nonlinear relationship between N_2O emissions and soil organic C, suggests that agricultural soils with higher organic C yield lower N_2O emissions (Huang et al., 2002). Huang et al. (2002) proposed that the higher C in soils would positively influence the reduction of N_2O to N_2 in consequence of a higher content of electron donors. The organic C content of the two soils in this study (Table 1), was slightly different and that also could be one of the factors for the lower N_2O emissions from Vertisols than Alfisols. Generally Vertisols have higher clay content, poorly drained and have a low hydraulic conductivity, while Alfisols are sandy loam to sandy clay loam in texture, and the soils are moderately to well-drained with reasonable hydraulic conductivity. High $N_2O/(N_2O+N_2)$ ratios are the characteristic of fairly well-aerated soils, in which N_2O can easily diffuse away, and thus is not further reduced to N_2 by denitrifying organisms (Webster and Hopkins, 1996). In the case of Vertisols, the poor drainage of these soils may limit gas diffusion, thus, the N_2O formed following nitrification and denitrification processes in the saturated soil moisture regime might have been reduced to N_2 before it could escape to the soil–air interface. Further, the activity of N_2O reductase enzyme is generally thought to increase with increasing pH values (Chapuis-Lardy et al., 2007). Thus, the high pH of the Vertisols (8.3) might have increased the activity of N_2O reductase enzyme, resulting in lower N_2O emissions. Li et al. (1992) and Velthof et al. (2002) reported that an increase in clay content decreased N_2O emissions because of the effect of clay on the soil hydraulic properties. The results of this study may suggest that somewhat poorly aerated soils under fertilizer N application may emit less of the applied N as N_2O than well-aerated soils.

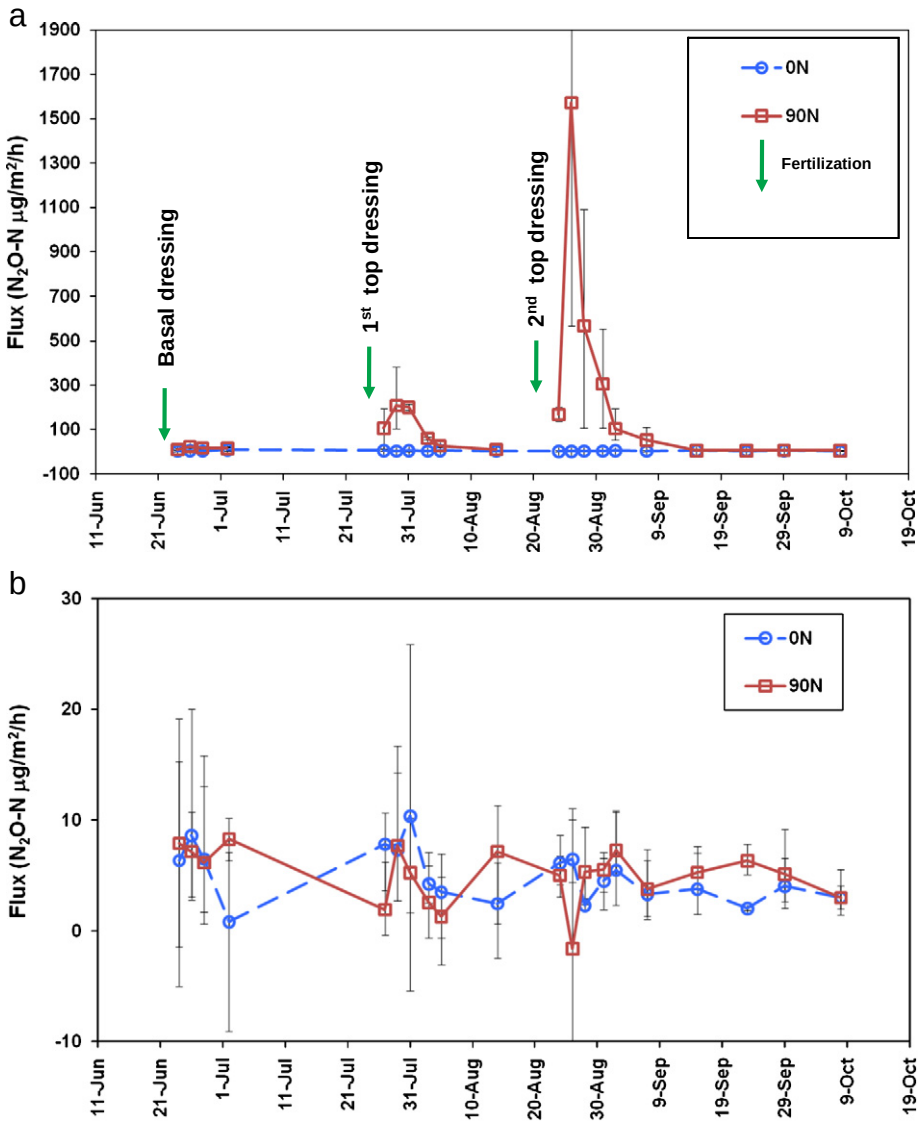

Fig. 3. Changes in N_2O emissions from (a) ridges (b) furrows on Alfisol field cultivated with sweet sorghum. The vertical bars show the range of the flux in triplicate measurements. 0 N: represents N_2O emissions from plots with no nitrogen application; 90 N: represents N_2O emissions from plots fertilized with 90 kg N/ha.

Table 2
Cumulative N_2O fluxes (N_2O–N kg/ha) (mean ± SD) from Alfisols and Vertisols during sweet sorghum cultivation.

N treatment	Position	Field	
		Alfisol	Vertisol
0 N	Ridge	0.15 ± 0.05	0.09 ± 0.02
	Furrow	0.11 ± 0.05	0.075 ± 0.06
90 N	Ridge	1.81 ± 0.75	0.70 ± 0.23
	Furrow	0.16 ± 0.02	0.10 ± 0.03
ANOVA			
F		**	
N		***	
N × F		**	
P		***	
P × F		**	
P × N		***	
P × F × N		**	

F: Field; R: Replication; N: N treatment; P: Position.
*** Significant at 0.01 probability level.
** Significant at 0.05 probability level.

3.6. Loss of applied nitrogen as N_2O

For calculation of emission factors of N_2O, the N_2O emissions measured from the ridges only were taken into account. Further, it was assumed that the N_2O flux measured at the time of sampling represented the average flux of the measured day. On the days when gas sampling was not conducted, the N_2O fluxes were calculated by linear interpolation between sampling occasions. For periods before the fertilizer application when measurements were not made, the background N_2O flux values were substituted. Based on these assumptions, the N_2O–N emission was integrated for the entire experimental period.

The emission factor for N_2O was calculated based on the definition by Intergovernmental Panel on Climate Change (IPCC) (2006):

$$EF = (E - Eo)/N \times 100$$

where E and Eo are N_2O emission from plots with and without N fertilizer application, respectively. N is the total amount of N application over the entire growing season. From the calculations, it was found that 0.90% of the applied N was lost as N_2O from Alfisols, and 0.32%

of the applied N was lost from Vertisols. The emission factors for N_2O are in broad agreement with the values reported in the literature. For example, Hellebrand et al. (2008) found the mean direct fertilizer-induced emissions during energy crop cultivation on loamy sand soils to be between 0.30 and 0.40%. Pathak et al. (2002) reported that 0.38% of applied N was lost as N_2O from the rice-wheat systems of the Indo-Gangetic plains of India. However, the proportion of N fertilizer applied that was lost as N_2O from canola crop in a semi-arid region of south-western Australia was only 0.06% (Barton et al., 2010).

The current emission factor approach using the IPCC methodology may not reflect the complex processes controlling soil N_2O flux. According to the IPCC default emission factor, 1.25% of fertilizer N is emitted as N_2O. This study reveals the importance of employing regionally specific emission factors when assessing GHG emissions as there are distinct regional differences in N_2O emission factors.

4. Conclusions

To our knowledge this is the first report on N_2O emissions from agricultural soils in this semi-arid region. It was found that 0.90% of the applied nitrogen was lost as N_2O from Alfisols and 0.32% of the applied nitrogen was lost from Vertisols. Our results suggest that N_2O emissions are greatly dependent on the soil properties. Although, the weather conditions were identical and similar agricultural management practices were followed for sweet sorghum cultivation in Alfisols and Vertisols, the emissions of N_2O were different in these two soil types. Therefore, the monitoring of N_2O emissions from different agro-ecological regions, having different soil types, rainfall characteristics, cropping systems and crop management practices are necessary to develop comprehensive and accurate GHG inventories.

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